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The X-ray emission lines in GRB afterglows: the evidence for the two-component jet model

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Abstract Recently, X-ray emission lines have been observed in X-ray afterglows of several γ-ray bursts. It is a major breakthrough for understanding the nature of the progenitors. It is proposed that the X-ray emission lines can be well explained by the Geometry-Dominated models, but in these models the illuminating angle is much larger than that of the collimated jet of the γ-ray bursts(GRBs). For GRB 011211, we obtain the illuminating angle is about $\theta \sim 45°$, while the angle of GRB jet is only 3.6°, so we propose that the outflow of the GRBs with emission lines should have two distinct components. The wide component illuminates the reprocessing material, and produces the emission lines, while the narrow one produces the γ-ray bursts. The observations show that the energy for producing the emission lines is higher than that of the GRBs. In this case, when the wide component dominates the afterglows, a bump will appear in the GRBs afterglows. For GRB 011211, the emergence time of the bump is less than 0.05 days after the GRB, it is obviously too early for the observation to catch it. With the presence of the X-ray emission lines there should also be a bright emission component between the UV and the soft X-rays. These features can be tested by the $Swift$ satellite in the near future.

Key words: gamma rays:bursts-line:profiles-ISM:jets and outflows-supernovae:general

1 INTRODUCTION

Gamma-ray bursts(GRBs) are commonly interpreted in terms of a relativistic outflow emanating from the vicinity of a stellar neutron star or black hole(e.g. Piran 2004; Zhang & Mészáros 2004). Highly collimated narrow jets can be inferred from the presence of achromatic breaks in the afterglow lightcurves(Rhoads 1999).

Recently X-ray emission lines have been observed in X-ray afterglow of several GRBs. They can provide important clues for identifying the nature of the progenitors of long (t≥2 s) GRBs. The first marginal detection of an emission line was in the X-ray afterglow of GRB 970508 with the BeppoSAX NFI (Piro et al. 1999). Later emission lines were also detected in the X-ray afterglows of GRB 970828 (Yoshida et al. 2001) with ASCA; GRB 991216 (Piro et al. 2000) and GRB020813 (Butler et al. 2003) with Chandra; GRB 011211 (Reeves et al. 2002), GRB 001025A (Watson et al. 2002) and GRB 030227 (Watson et al. 2003) with XMM-Newton; GRB 000214 (Antonelli et al. 2000) with BeppoSAX. The detailed properties of the X-ray emission features can be found in several papers (Lazzati 2002; Böttcher 2003; Gao & Wei 2004). The locations of the emission lines found in the X-ray afterglows of GRB 970508, GRB 970828, GRB 991216 and GRB 000214 are roughly consistent with Fe K_α at the redshift of the hosts, while the emission lines were identified as blueshifted light elements lines of S, Si, Ar, Mg, and Ca in the afterglow of GRB 011211, GRB 020813 and GRB 030227.

Two main types of models have been put forward to interpret the emission lines: one is Geometry-Dominated(GD) models(e.g. Vietri et al. 2001; Lazzati et al. 1999; Reeves et al. 2002), the other is Engine-Dominated(ED) models(e.g. Rees & Mészáros 2000; Mészáros & Rees 2001). In ED models, the lines are created by reprocessing material very close to the explosion site(R$\sim 10^{13}cm$). The ionizing continuum is believed to be provided by a post-burst energy injection(Rees & Mészáros 2000; Mészáros & Rees 2001; Gao & Wei 2004, 2005). The duration of the lines emission is determined by the time interval of the post-burst energy injection. While in GD models the reprocessing material is located at a large enough distance($R \sim 10^{16}cm$), illuminated by the burst and early afterglow photons. In GD models, the duration of the emission lines is set by the size of the reprocessor. This reprocessing material is compact and metal enriched, similar to a supernova remnant, as predicted in the supranova model(Vietri & Stella 1998).

It is argued that the production of the emission lines strongly favors the GD models(e.g. Lazzati et al. 2002; Reeves et al. 2002). But in these models, either in the reflection model or in the thermal model, a large collimation angle of the illuminator is needed(e.g. Lazzati et al. 1999, Reeves et al. 2002).

The half opening angle of the GRB jet is obtained from the presence of the achromatic break in the afterglow lightcurve(Frail et al. 2001, Bloom et al. 2003), it is much smaller

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than the illuminating angle obtained with the GD models. If the photons of illuminating the reprocessing material comes from the bursts and early afterglows, with such small collimation angle, the duration time of the emission lines will be much shorter than that of the observations. It also contravenes the fact that much higher energy is needed for the illuminating continuum that is responsible for the lines production than that of the collimated GRBs(Lazzati 2002; Ghisellini et al. 2002; Gao & Wei 2004). To solve the energy problem, we have explained it as continuous post-bust energy injection from magnetar(Gao & Wei 2004), or delayed energy injection from central engine(Gao & Wei 2005), similar model can also explain the early flare in X ray afterglow light curve(Fan & Wei 2005).

Recently, two distinct components in the GRB outflow has been proposed for several gamma-ray bursts. On the observational side, Frail et al.(2000) proposed that the γ-rays and early X-rays and optical afterglow of GRB 991216 could be attributed to a narrow ultra-relativistic outflow component and the longer-wavelength afterglow such as radio afterglow originated in a wide component that is only mildly relativistic. A similar picture was proposed for GRB 970508(Pedersen et al. 1998) and GRB 030329(Berger et al. 2003; Sheth et al. 2003). A two-component model was also suggested as the explanation for the observation of the re-brightening of the X-ray flash source XRF 030723(Huang et al. 2004). In the numerical simulations of collapsar model, the narrow component has a Lorentz factor γ_n $\geq$100 and a half opening angle $\theta_n \sim 3^\circ - 5^\circ$, while for the wide component, γ_w $\sim$15 and $\theta_w \sim 10^\circ$(Zhang et al. 2004). In his GRMHD models of the jet formation, McKinney(2005) has found a two-component jet with a quite broad component out to 25° and a core component within 5°.

In this paper, we reconsider the Geometry-Dominated models, and investigate the angle of the illuminator in GRB 011211 afterglow. A large illuminating angle is obtained. Here we propose a two-component outflow model to solve the angle problem. We propose that the outflow in the GRB whose afterglow shows the lines emission has two components, the angle of the wide component is about several tens degrees, and the energy of the wide component is high enough to illuminate the material to produce the emission lines.

2 THE ILLUMINATING ANGLE AND THE TWO-COMPONENT JET MODEL

In this paper the Geometry-Dominated models are used to explain the lines production(e.g. Lazzati 2002, Lazzati et al. 2002). In these models the lines emission comes from an extended region and its duration arises from light-travel time effects. So the geometry of the dense material is important because it dominates the time duration of the

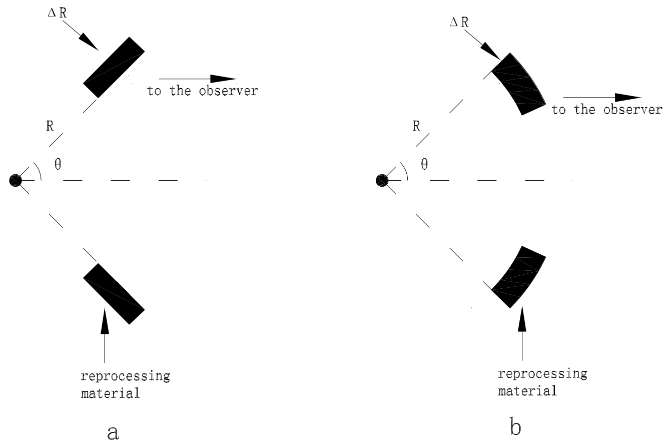

Fig. 1 Sketch of the geometry assumed for the reprocessing material in the Geometry-Dominated models. a: the funnel-shaped material in reflection model. b: the shell-shaped material in thermal model.

line emission. Lazzati et al.(1999) have investigated the relations between the geometry of the reprocessing material and the theoretical models.

Here we investigate the illuminating angle in the reflection model and thermal model. In the reflection model, the photons are reflected by the funnel-shaped material. Here we adopt the geometry of the reprocessing material similar to that adopted in the work of Tavecchio et al.(2004). This geometry of the material is efficient for the reflection, we called it funnel-shaped reprocessing material(Fig.1a). In the first subsection below, we re-calculate the illuminating angle in the reflection model. The detailed calculation of the physical quantities can be found in the paper of Tavecchio et al.(2004).

In the thermal model, similar to the geometry taken by Lazzati et al. (1999), we adopt the shell-shaped reprocessing material(Fig.1b). This geometry of the material is efficient to be heated to high temperature and produces the emission lines by collision-ionization and recombination. Though Reeves et al.(2002) have explained the production of the emission lines with the thermal model, an illuminating angle of 20° is only assumed(not calculated). In the second subsection below we calculate the illuminating angle of the burst source in the thermal model.

2.1 The illuminating angle in the reflection model

Here we reconsider the reflection model, similar to the calculation of Tavecchio et al.(2004). In the reflection model, with the funnel-shaped reprocessing material(Fig.1a), the time at which lines become visible can be defined as following(the time intervals are measured in the frame of the burst source):

$$t_{app} = \frac{R}{c}(1 - cos\theta), \qquad (1)$$

where θ is the half opening angle of the illuminator, R is the distance between the burst source and the reprocessing material.

The duration of the line t_{line} can be given by

$$t_{line} \sim \frac{\Delta R}{c} cos\theta, \tag{2}$$

where ΔR is the width of the reprocessing material, which can be expressed as (Tavecchio et al. 2004).

$$\frac{\Delta R}{R} = \frac{1}{5\pi}\xi\zeta\frac{W_i m_p}{A_i \epsilon_i sin\theta \alpha_r}, \tag{3}$$

where W_i is the atomic weight of the element(the subscript i denotes a specific line). ξ is the ionization parameter. For soft X-ray lines, ξ is about 10^2 for the efficient emission(Lazzati et al. 2002). For GRB011211, ionization parameter is

$$\xi = \frac{L_{ill}}{n_e R^2} \simeq 10^2, \tag{4}$$

here L_{ill} is the luminosity of the X-ray illuminating continuum. n_e is the number density of the electron. ζ is the efficiency in producing the lines(e.g. Ghisellini et al. 2002),

$$\zeta = \frac{E_{line}}{E_{ill}} \simeq 10^{-2}. \tag{5}$$

A_i is the mass abundance of the emitting element, ϵ_i is the energy of the line, α_r is

$$\alpha_r = 5.2 \times 10^{-14} Z \lambda^{1/2} [0.429 + 0.5 ln(\lambda) + \frac{0.496}{\lambda}^{1/3}], \tag{6}$$

where $\lambda = 1.58 \times 10^5 Z^2 T^{-1}$, Z is the atomic number of the element and T is the electron temperature. For GRB 011211, the temperature T of a photoionized plasma illuminated with $\xi = 100$ is predicted to be in the range $10^5 - 10^6$K(e.g. Kallman & McCray 1982). Here we then assumed $T = 5 \times 10^5$K.

Combing Eq. (1)-(3), it can be found that

$$tan\theta(1 - cos\theta) \sim \frac{1}{5\pi}\xi\zeta\frac{W_i m_p}{A_i \epsilon_i \alpha_r}\frac{t_{app}}{t_{line}}. \tag{7}$$

For GRB 011211, the observation shows that the emission lines appear at time $t_{app} \leq 4 \times 10^4/(1+z)s \sim 1.3 \times 10^4 s$, and the time duration of the lines $t_{line} \simeq 5 \times 10^3/(1+z)s \sim 1.7 \times 10^3 s$. $\xi \simeq 100$ and $\zeta \simeq 0.01$. For the solar abundance of the elements(Anders & Grevesse 1989), we can know the value of A_i. ϵ_i is the center energy of the line. For instance, ϵ_{CaXX} is 4.70 KeV(in the burst source frame). In this case, the illuminating angle can be obtained about $\theta \sim 45°$.

2.2 The angle of the illuminator in the thermal model

In the thermal model, for the shell-shaped reprocessing material(Fig.1b), the duration of the lines observed in the GRB afterglow is

$$t_{line} = \frac{R}{c}(1 - cos\theta). \quad (8)$$

The X-ray lines luminosity is

$$L_i = [N_i \epsilon_i / t_{rec}](1 + z)^{-1}, \quad (9)$$

where N_i is the number of specific element nuclei. t_{rec} is the recombination time scale. When the reprocessing material is heated to thermal equilibrium, close to the Compton temperature $T_C \sim 10^7 K$(Reeves et al. 2002), we can get that $t_{rec} \sim 10^{11} T_7^{1/2} n_e^{-1}$.

The number of specific element nuclei in the material layer within Thomson optical depth τ_T=1(in $\tau = 1$ layer, the material absorbs enough energy without smearing the lines very much(see Gao & Wei 2005)) is

$$N_i \sim A_i M / (\tau_T W_i m_p), \quad (10)$$

where M is the total mass of the material that is illuminated by the illuminator. $M = n_e m_p V$, V is the volume of the illuminated material, and $V = 2\pi R^2 (1 - cos\theta)\Delta R$. τ_T is Thomson optical depth of the reprocessing material, $\tau_T = n_e \Delta R \sigma_T$.

For GRB 011211, the ionization parameter $\xi \simeq 10^2$(Lazzati et al. 2002), the X-ray luminosity illuminating the material is of the order $L_{ill} \sim 10^{47} ergs^{-1}$. The luminosity of the line is about $10^{45} ergs^{-1}$, $t_{line} \sim 1.7 \times 10^3 s$. According to these, we can get $\theta \sim 45°$.

We have obtained the angle of the illuminator, that is about 45°. Obviously it is much larger than the half opening angle of the GRB jet, that is only 3.6°(Frail et al. 2001; Bloom et al. 2003).

Therefore, we propose that the outflow of the GRB with the X-ray lines has two distinct components: the narrow one produces the prompt GRB emission, while the wide component illuminates the reprocessing material and produces the emission lines. The illuminator's angle is $\theta \sim \theta_w$.

3 PRODUCTION OF THE BUMP IN TWO-COMPONENT OUTFLOW

It has been found that the energy obtained from the lines emission is higher than that of the γ-ray burst(Ghisellini et al. 2002; Gao and Wei 2004). So in two-component outflow model, the energy of the wide component illuminating the reprocessing material should be $E_{ill} \sim E_w \geq E_n$, E_n is the energy of the narrow component, that is the same as that of the γ-ray burst, $E_n = E_\gamma$.

In the theory of GRB afterglow, the interaction of the jet with the ambient medium drives a reverse shock into the GRB ejecta, which decelerates the ejecta. The energy given

to the swept-up external medium is about $\sim \eta^2 M_{sw} c^2$(Here, η is the Lorentz factor of the outflow; M_{sw} is the rest mass of the swept-up external medium). We assume that the Lorentz factor of the GRB jet(i.e. the narrow component) is $\eta_n \sim 300$. The energy in the wide component is more than that of the narrow component, $E_w \geq E_n$. We assume that the density of the medium in the wide component is the same with that in the narrow component. So we can assume $\eta_w \geq 30$(η_w is the Lorentz factor of the wide component).

From the work of Peng er al.(2005), for $E_w/E_n > 1$, we expect that a bump should be found in the afterglow at the time $t_{dec,w}$(the deceleration time of the wide component) when the wide component dominates the afterglow. That is

$$t_{dec,w} \leq 0.05(\frac{E_{iso,52}}{n_0})^{1/3}(\frac{\eta_w}{30})^{-8/3} days. \tag{11}$$

So we should observe the bump at about less than 0.05 days after the γ-ray burst. The GRB 011211 X-ray afterglow is observed about 11 hours after the burst(Reeves et al. 2002). Obviously it is too early to observe the bump.

If the energy of the wide component is less than or comparable with that of the narrow component, the lightcurves of the afterglow would not be dominated by the wide component, so the bump would not appear. Only when the energy of the wide component is much higher than that of the narrow one, the bump would distinctly emerge(Peng et al. 2005; Wu et al. 2005).

4 DISCUSSION AND CONCLUSIONS

The Geometry-Dominated models have been proposed to explain the X-ray emission lines observed in the X-ray afterglows (e.g. Lazzati et al. 2002, Reeves et al. 2002). In these models, the time duration is set by the geometry of the reprocessing material. In this paper, we investigate the Geometry-Dominated models and calculate the illuminating angle of the illuminator.

Generally iron line can be well explained in reflection model while soft X-ray lines prefer the thermal model. Of course, this is not absolute. Tavecchio et al.(2004) have claimed that emission lines in GRB 011211 afterglow also can be well explained in reflection model. So in this paper, we calculate the illuminating angle in reflection model and thermal model respectively.

For GRB 011211, in the GD models, an illuminating angle $\theta \sim 45^\circ$ is obtained. However from the presence of the break in the light curve of GRB afterglow, the jet of GRB 011211 with angle only $\theta_j \sim 3.6^\circ$ has been obtained(Frail et al. 2001; Bloom et al. 2003).

Since it is comparable for the physics parameter of X-ray lines on the whole(Lazzati 2002), we assume that the illuminating angle in other GRBs has the same case as in GRB 011211.

It should be noted that solar abundance of the line element is adopted in our calculation. The angle would be smaller than $45°$ if we adopt lager element abundance. For instance, if we adopt 10 times solar abundance of the line element, we can get $\theta \sim 22°$. But in any case it will be lager than the half opening angle of GRB 011211.

Therefore we proposed two-component outflow model in the γ-ray burst with X-ray emission lines. The angle of the wide component is comparable with that of the illuminator, $\theta \sim 45°$; while the collimated jet of the GRB is comparable with the narrow component, $\theta_j \sim 3.6°$.

For GRB 011211 the energy for illuminating the reprocessing material obtained from the X-ray lines is higher than 5×10^{50}ergs(Gao and Wei 2004; Ghisellini et al. 2002), which is higher than that of the γ-ray bursts. In this case, the wide component will dominate the afterglow, a bump will appear in the lightcurve of the afterglow. Our calculation shows that it should be seen at about less than 0.05 days after the burst in the X-ray afterglow. Unluckily it was too early to be observed.

In this two-component outflow model, when the wide component dominates the lightcurve of the afterglow, an approximate isotropic component of the X-ray afterglow should be observed. In the X-ray band observation of GRB 011211 afterglow, no break in the afterglow was reported(Reeves et al. 2002).

For GRB 991216, a narrow half opening beaming angle $\theta_j \sim 3°$ has been claimed from the optical observation(Halpern et al. 2000). But recently Ruffini et al.(2005) have claimed that the data analysis in the 2-10 KeV of GRB 991216 afterglow conformed spherical symmetry. We have calculated the energy of the illuminator obtained by the emission lines. It is between 3×10^{51} and 3.8×10^{52}ergs(Gao and Wei 2004). This energy is much higher than that of the burst. So the bump would appear in the lightcurve of the afterglow. But it is too early for the observation to be observed. When the wide component dominates X-ray afterglow, a spherical symmetry afterglow would be obtained. So the result obtained by Ruffini et al.(2005) is consistent with our two-component outflow model.

In the same way, our two-component model is also consistent with the observation of GRB 970508, whose afterglow could be explained in terms of a narrow jet surrounded by an isotropic outflow(Pedersen et al. 1998).

In the low-ionization condition discussed here, about 90% of the total incident luminosity is absorbed by the reprocessing material(e.g. Zicky et al. 1994), and that will be re-emitted. The reprocessed luminosity L_{repr} is about

$$L_{repr} = 0.9\frac{L_{line}}{\zeta} \sim 9\times10^{46}\frac{L_{line,45}}{\zeta_{-2}}ergs^{-1}. \tag{12}$$

The surface of the slab illuminated by the incident continuum will be heated to high temperature, close to the Compton temperature $T_C \sim 10^7K$(e.g. Reeves et al. 2002). The emission from these outer layers will peak in the X-ray region, at energies around 1

KeV. Gas in the layers deeper in the material will be close to the thermal equilibrium: the temperature of these region will be close to the black-body temperature corresponding to a black-body emission with the luminosity of the order $L_{bb} = L_{repr}$. Tavecchio et al.(2004) have obtained that the maximum of the emission falls at the frequency $\nu_{bb} \sim 10^{15}$ Hz, i.e. in the near UV.

The actual outcoming spectrum will be a complex integral over the emission from the different layers, in time-dependent conditions. The detailed calculation of the spectrum is beyond the scope of this paper.

So, accompanying with the presence of the X-ray emission lines there should be a bright component between the UV and the soft X-rays, that is 100 times larger than the line luminosity(Tavecchio et al.2004).

In conclusion we assume that the outflow of GRBs has two components. The wide component illuminates the reprocessing material, and produces the emission lines; while the narrow component is corresponding to the jet of GRBs. We have obtained that for GRB 011211 the bump should be observed at less than 0.05 days after the burst because of the higher energy of the wide component, but it was too early for the bump to be observed. A bright component between the UV and the soft X-rays should also be observed with the presence of the X-ray emission lines.

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